Team Reports: Carnegie Institution of Washington

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Executive Summary
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The NAI team led by the Carnegie Institution of Washington is studying the evolution of organic compounds from prebiotic molecular synthesis and organization to cellular evolution and diversification. Our program attempts to integrate the sweeping narrative of life's history through a combination of bottom–up and top–down studies. On the one hand, we study processes related to chemical and physical evolution in plausible prebiotic environments – the interstellar medium, circumstellar disks, extrasolar planetary systems, the primitive Earth, and other Solar System objects. Complementary to these bottom–up investigations of life's origin, we carry out field and experimental top–down efforts to document the nature of microbial life at extreme conditions and the characterization of organic matter in ancient fossils. Both types of efforts inform our development of biotechnological approaches to life detection on other worlds.

Our team's research activities focuses on life's chemical and physical evolution, from the interstellar medium, through planetary systems, to the emergence and detection of life, across seven integrated areas of research:

1. We are applying theory and observations to investigate chemical evolution in the interstellar medium, in circumstellar disks, during planetary formation, and on Solar System bodies.

2. We are carrying out analytical research on extraterrestrial samples, including meteorites and interplanetary dust particles, with an emphasis on organic molecules and evidence for water.

3. We are studying prebiotic chemical and isotopic evolution on Earth, with an emphasis on the sulfur cycle and the role of sulfur in prebiotic organic synthesis.

4. We are investigating possible mechanisms of prebiotic molecular selection and macromolecular organization, including the self–organization of amphiphiles and the selective adsorption of organic molecules onto mineral surfaces.

5. We are continuing to study life in extreme environments, with field

studies of hydrothermal microbial communities and laboratory studies of stress adaptation of microbes in high–pressure and high–temperature environments.

6. We are examining ancient fossils and microbes fossilized in the laboratory with a variety of analytical techniques to assess preservation mechanisms of molecular biosignatures, and we are studying modern geothermal systems to investigate preservation of biosignatures during silicification in these environments.

7. We are applying our enhanced understanding of life's chemical and physical evolution to develop new techniques in astrobiotechnology – procedures that will be applied to the design and testing of instruments for life detection, initially in terrestrial settings and eventually on spacecraft to be sent to other Solar System bodies.

Fuller understanding of life's origin, evolution, and distribution requires major advances on all these topics, as well as the extensive challenge of integrating these topics. During the past year we achieved significant progress in each of these research areas, and we devoted increased attention to the interfaces among these theoretical, experimental, and field approaches.

Among the highlights from the past year's research in the area of the evolution **from molecular clouds to habitable planetary systems** were the following:

- Observations of circumstellar disks in the TW Hydrae and Beta Pictoris associations show that evidence for inner disk clearing is not a simple function of the age of the association.
- Theoretical models of convective energy fluxes in circumstellar disks strongly support the idea that giant planets may form rapidly by the disk instability mechanism.
- Models for the delivery of water–bearing planetesimals to the growing terrestrial planets shows that the efficiency of this process depends sensitively on the presence of the giant planets.
- Continued radial velocity measurements of the 2,000 Sun–like stars within 50 parsecs have yielded a number of new extrasolar planet candidates, including a planet with a minimum mass twice that of Jupiter orbiting its Sun–like star (HD 70642) on a nearly circular orbit at a distance of 3.3. AU. The system is the closest analog of our Solar System discovered to date.
- New models for the atmospheres of hot Jupiters have laid the groundwork for understanding the results of future observations of hot Earths.

Highlights in the area of **extraterrestrial materials and the origin and evolution of organic matter in the Solar System** during the past year included the following:

- The first confocal Raman images of interplanetary dust particles permitted three–dimensional mapping of organic matter at the 200–nm scale.
- D/H isotopic imaging of carbonaceous chondrites demonstrates more extreme heterogeneity on the 1–2 µm scale than previously recognized. In general, however, the D/H ratio of organic matter in carbonaceous chondrites correlates strongly with the extent of parent body processing.

- Petrographic, isotopic, and transmission electron microscopy (TEM) measurements of a partially differentiated meteorite indicate that carbon isotope heterogeneity in graphite can be preserved during partial melting in meteorite parent bodies.

Highlights in the area of **prebiotic chemical and isotopic evolution on Earth** during the past year included the following:

- Sulfur fractionated by enzymatic catalysis has been harvested in the laboratory from living culture of sulfur−matabolizing microbes and analyzed for ^{32}S−^{33}S−^{34}S.
- A model that describes the mass−dependent sulfur isotope fractionations for sulfate reducers and sulfur disproportionators has been developed that shows how microbes may have played a crucially important dual role in both preserving but also diluting anomalous sulfur isotope fractions. As an agent of preservation, microbial enzymatic catalysis precipitates pyrite, a secure storage site for sulfur isotopes, but as an inhibitor, the full magnitude of isotope anomalies may not be preserved because of dilution.
- Many common transition−metal sulfides have been shown experimentally to catalyze organic reactions in a manner that mimics the carbon fixation pathways adopted by acetogenic and methanogenic microorganisms.

Highlights in the area of **prebiotic molecular selection and organization** during the past year included the following:

- The facile self−assembly and vesicle formation of amphiphiles was demonstrated during hydrothermal reactions of pyruvate.
- A novel hypothesis, dubbed the “PAH world,” provides a plausible chemical link from the random prebiotic “soup” to the RNA world. By the PAH world hypothesis, polcyclic molecules self−assemble into stacks and then selectively bind purines and pyramidines, the bases of nucleic acids.
- Atomic force microscopy measurements support the inference that electrostatic interactions dominate the selective adsorption of amino acids by mineral surfaces.
- More than a dozen common chiral mineral surfaces have been identified and characterized with respect to their potential for prebiotic selection of chiral molecules. Adaptation of DNA ChipWriter/ChipReader technology to the study of molecular adsorption on mineral surfaces promises to speed future such efforts.

Highlights in the area of **life in extreme environments** during the past year included the following:

- Bacterial groups were discovered that are unique to the hot environments of mid−ocean ridge hydrothermal vents and include new groups of microorganisms that can fix carbon dioxide in the absence of oxygen with hydrogen and sulfur.
- The Lost City hydrothermal field represents a new type of submarine hydrothermal system driven by exothermic chemical reactions in mafic oceanic crust and not as the result of cooling magma.
- Studies of microorganisms within sulfide chimneys at active hydrothermal vents suggest that biofilm formation on minerals may be associated with microbial growth or survival at extremely high temperatures.

- Laboratory experiments have demonstrated that microbes are able to survive at pressures where ice−VI is observed.
- Diamond anvil cells are being designed to allow manipulation of cells and organic material after exposure to extreme pressures.
- A possible connection has been uncovered between the isotopic composition of Fe and the degree of microbial Fe processing in Fe−bearing bacterial mats.

Highlights in the area of **biosignatures and abiosignatures** during the past year included the following:

- Molecular analysis of biofilms from the Enspel Formation reveals that within the aliphatic fractions there are distinct compositional differences between the biofilms and the sediment.
- Compound−specific isotope ratio mass spectrometric analysis of amino acids suggests that discrete metabolic pathways may have distinct isotopic signatures.
- A substantial database of C, N, O, and H isotopic biosignatures from the early Cambrian is being developed.

Highlights in the area of **astrobiotechnology** during the past year included the following:

- Life−detection instrumentation has been tested in a Mars analog environment on Svalbard. This environment will be used to test flight instrumentation proposed for Mars lander missions.
- Fossil collagens in 40,000−year−old bone samples have been characterized using the world's first antibody microarray to fossil compounds.
- High throughput has been achieved for the simultaneous screening of thousands of fluorescently labeled D and L amino acids for assessing their binding characteristics to mineral surfaces.
- Quantitative microfluidic cell lysis has been demonstrated for gram−negative, gram−positive, and archaeal cells.

In summary, our team's recent research, including discoveries and characterization of new planetary systems, investigation of the fates of carbon and water on planetary building blocks and other worlds, elucidation of robust pathways for prebiotic organic synthesis, documentation of novel microbial metabolic strategies, evaluation of possible biosignatures, and development of new technologies for astrobiological exploration, inform the central questions of astrobiology. Taken together, these discoveries are changing our views of life's origin and its possible distribution in the universe.